Missile Launcher System Dynamic Design Criteria

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Abstract - Missile Launcher system is an assembled store carried externally on the rotor craft (Helicopter). The main objective of present study is to design launcher system to the dynamic environment created due to the main rotor of the helicopter, and hence it is an apt case of design for dynamic environment. The mass of launcher should not exceed 20 kg. Launcher system designed as a modular construction, considering the ease of assembly, quick loading and unloading of the missile launch tubes and replacement requirement of accessories. The launcher frame is made up of members, having hollow box-type cross-sections. Box-section has been chosen after initial iterations of open I-section indicated low frequency torsion modes. The box-section has high torsion rigidity compared to the open I-section. Most important input which dictates the design of launcher system is the launcher system structural resonant frequencies, which should not match with helicopter main rotor frequencies. To ascertain this requirement modal analysis has been carried out on the initially designed configuration and iterated the design till it meets the design constraints. Sine-on-random vibration input was constructed by superimposing the broadband random excitation with sinusoidal excitation coming from the helicopter main rotor frequencies. Response analysis has been carried out using the modal analysis output data and sign-on-random excitation. Constant damping ratio is used for analysis. The maximum 1σ displacements, 1σ acceleration and 1σ stresses for the launcher are computed using finite element analysis and factor of safety are reported. The 1σ stress results shows that the launcher has a minimum required factor of safety. The response results shows that the amplifications in amplitudes for vibration input are within the permissible range. The separation has been maintained between launcher frequency and the rotor's critical frequencies. The study demonstrates the need for considering the dynamic design criteria for missile launcher system.

Keywords - Missile launcher; Helicopter launch; Dynamic loading, Base excitation, Random vibration, PSD, Spectrum, Natural frequencies, Resonance, Modal analysis, Response analysis.

I. INTRODUCTION

Missile launcher system is an assembled store carried externally on the Helicopter. Design of the launcher system necessitates that due considerations be given to the dynamic environment created due to main rotor of the helicopter. Other than strength based design the very important requirement for helicopter launcher system design is to avoid match of the launcher structural resonant frequencies with the helicopter excitation frequencies.

Various researchers have presented their work related to launcher design, however each one is peculiar to particular situation. Wanhill et al. [1] discusses five helicopter accidents with evidence of material and/or design deficiencies. Pezzella [2] shown the launcher concept designed for vertical takeoff, the vehicle architecture shows a circular cross section with a loft fillet on the belly side to accommodate both the wings and the body flap. Fragile Joseph R [3] discusses about the safety of crewed launchers and emphasized the need for number of test flights to get the desired safety level. Nechitailo et al. [4] emphasized the importance of considering structural resonance during launcher design. It is shown that the various components of a launcher can have different critical velocities and there is a possibility of enhanced group resonance in the assemblies. Ross Carl T.F [5] presents a conceptual design of an underwater missile launcher. Military Standard, MIL-STD-810F [6] describes the environmental test methods and engineering guidelines. General structural and mechanical design criteria for airborne stores, suspension equipment and their associated interfaces are discussed in Military Specification [7]

This paper describes the intricacies of the design and analysis of missile launcher system on helicopter. Load estimation, configuration design, finite element analysis, power spectral density analysis and results are discussed. The launcher has been realized, tested and used in flight trials.

II. DESIGN CRITERIA

Configuration design of the launcher was carried out based on the attachment to helicopter, weight of launcher, ease of assembly, disassembly, locking and provision for the accessories mounted on the launcher such as electronics and cooling system. The launcher system, by virtue of its attachment position on the armament boom falls in the vertical projection of the main rotor disc of the helicopter. Missile launcher system on helicopter is shown in Fig.1 The source of excitation frequencies, in addition to the broad band excitation will be the first four frequencies of the main rotor disc of helicopter. The launcher system structural resonant frequencies should not match with these main rotor frequencies. This is the single most important input, which dictates the design of the launcher system. Dynamic analysis carried out for this load case. Static (inertial) load is considered which will be due to maneuvering/ hard landing of the helicopter. This static analysis carried out separately. The launcher should be structurally withstanding both the static loading and dynamic vibration environment of helicopter.

III. LOADING ENVIRONMENT

External stores and the associated interfacing hardware have been designed to withstand the most critical combinations of aerodynamic, dynamic and inertial loadings. The loads acting on launcher classified in two cases namely Dynamic and Static loading are described in next section.

A. DYNAMIC LOAD

Externally mounted helicopter launcher receive aerodynamic excitation, this is generally random in nature. The dynamic load [6] is estimated which include sinusoidal excitation in addition to random loading. These two loads are simultaneously applied on launcher. Sine-on-random vibration input was constructed by superimposing the broadband random excitation with sinusoidal excitation coming from the helicopter main rotor frequencies. Sine-on-random acceleration PSD (g2/Hz) as discussed is applied in all three X,Y,Z directions. Sine-on-Random vibration input plot is shown in Fig. 2.

B. STATIC LOAD (INERTIAL LOAD)

The launcher experiences inertial loading during flight maneuvers and during landing. The load factors used to calculate the inertial loading are an algebraic sum of the load factors due to linear and angular accelerations. The linear load factors for maximum maneuver condition and hard landing conditions are considered. The load factors [7] due to angular accelerations are calculated.

The landing load factors are more severe as compared to the maneuver load factors. Landing loads cannot be combined with aerodynamic loads. Hence, the most severe steady-state loading environment is due to the hard landing scenario. Load factors are positive when acting aft, to the right (looking forward) and up. The overall load factors due to inertial loading of the launcher are given in Table-1.

Fig. 1 Missile launcher system on Helicopter

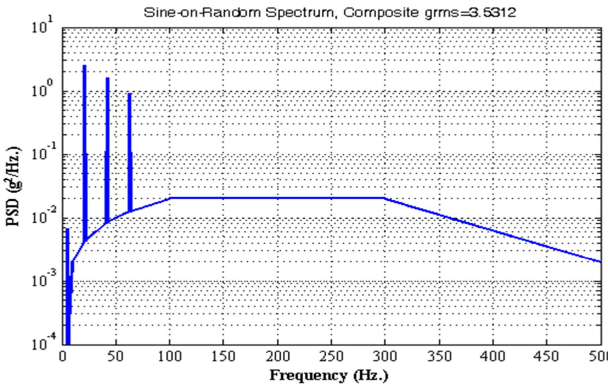


Fig. 2 Sine-on-Random vibration input

TABLE-I OVERALL LOAD FACTORS DUE TO INERTIAL LOADING OF THE LAUNCHER

Direction	Linear Load Factor (g)	Rotational Load Factor (g)	Overall Load Factor (g)
Forward	- 3.0	- 2.52	- 5.52
Right side (looking forward)	+ 2.0	+ 2.08	+ 4.08
Downward	- 7.0	- 3.00	- 10.00

IV. LAUNCHER CONFIGURATION DESIGN

The designed launcher system is a twin launcher, which can carry two missiles. The cooling system required for cooling of the IR sensor is attached with the launcher. Launcher system configuration is as shown in Fig.3 The launcher system carrying two missiles is designed as a modular construction, considering ease of assembly, quick loading and unloading of missile launch tubes, purging of missiles and replacement requirement of cooling bottle. The launcher system consists of three basic line replaceable units (LRUs) as listed below.

LRU-1: Release Unit mounting assembly.

LRU-2: Launcher Frame with Cooling System and Launcher Interface Unit

LRU-3: Launch Tube Assembly (including missile)

LRU-1 attaches the launcher frame assembly with the armament boom. Design of this unit LRU-1 is not included in this study. LRU-2 is the basic launcher frame, which is a box construction structure, made up of two bottom boxes and a top box, which are attached to three Central Plates by fasteners. The lifting lugs and the crutch arm supports are attached to the top box and LRU–3 rests on the two bottom boxes. Two spring loaded locking plungers, one on each of the rear bottom boxes is provided to engage the launch tube assembly (LRU–3). This arrangement facilitates quick loading and unloading of the launch tube assembly. Cooling System and electronics are mounted on a mounting plate, which is attached to the three Central Plates of the Launcher Frame. LRU-3 is the launcher tube assembly, consists of a missile and a composite launch tube. Design of this unit LRU-3 is also not included in this study.

V. FINITE ELEMENT ANALYSIS

3D modelling of the launcher system including lifting lugs, crutch arm supports is carried out in SOLIDWORKS and exported to ANSYS for finite element analysis. Due to complex geometry of Launcher it is not possible to discretize using beam or shell elements, hence, Launcher system is descretized using 10 noded tetrahedron solid elements. The missile is modelled using 3D beam elements. The intersection joints are modelled using spring element. The missile mass is lumped using MASS21 element.

The lifting lug is carried by a hook on the releasing unit which in turn is mounted on the armament boom of helicopter. On the other side, the lifting lug is screwed into the crutch arm support. This arrangement does not allow the twin launcher system to sway as rigid body in any direction. This is incorporated in the finite element model by providing fixed boundary conditions at the eye of the lifting lug and on the pressure pad seating locations of the crutch arm support. The finite element mesh model with boundary conditions is as shown in Fig. 4

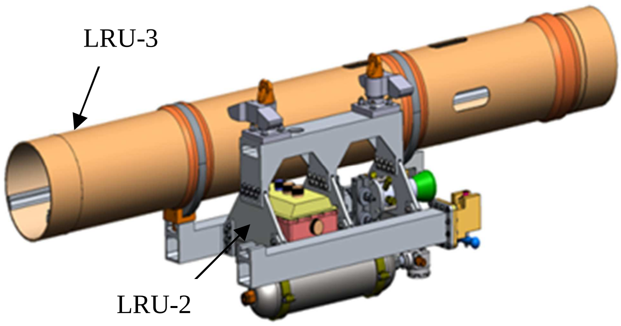


Fig. 3: Launcher system configuration (LRU-1 not shown)

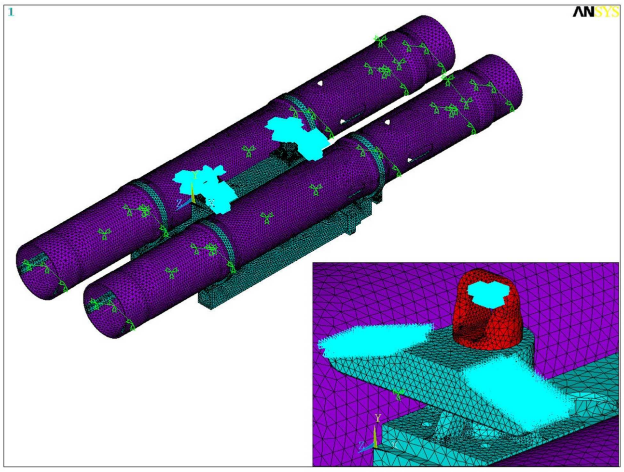


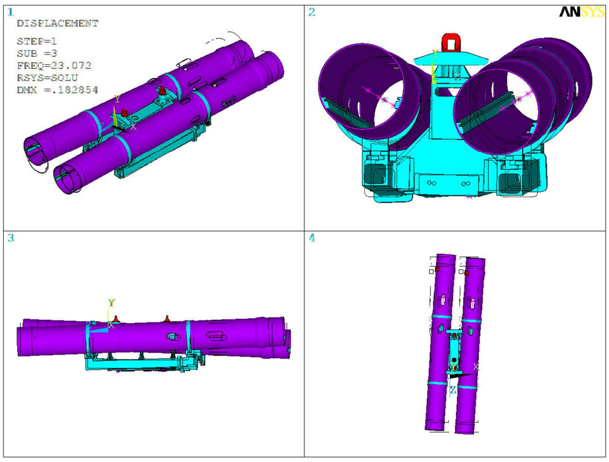
Fig. 4 Finite element model and boundary conditions

A. *MODAL ANALYSIS*

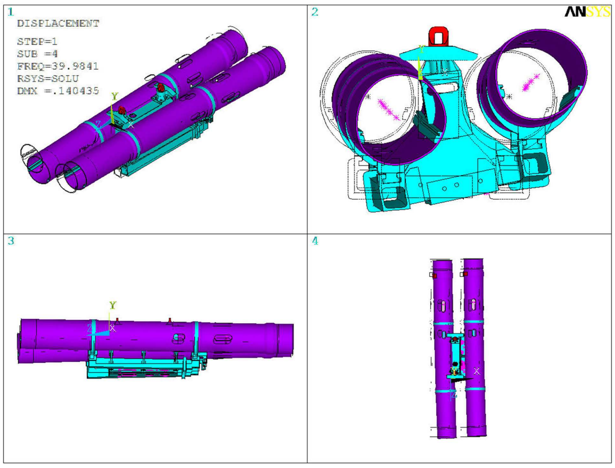
Modal analysis of the launcher is carried out using ANSYS and extracted the frequencies which fall in the range of 0-500 Hz using Block Lanczos method. Modal frequencies of launcher are given in Table-2. First two mode shapes are given in Fig.5 For each mode 04 views are shown.

Table-2. Frequencies of the launcher

MODE	Frequency (Hz)
1	23.1
2	40.0
3	44.7
4	47.7
5	56.2
6	60.1



Mode-I 04 views (Frequency 23.1 Hz)



Mode-II 04 views (Frequency 40.0 Hz)

Fig. 5 First two natural modes of the launcher system

B. RANDOM VIBRATION ANALYSIS

Random response [8] is obtained by carrying out a spectral analysis of the launcher system subjected to sine-on-random excitation as base excitation. A spectrum analysis is one in which the results of the modal analysis are used with a known spectrum to calculate the response displacements and stresses.

Governing Equations

The vibratory energy, due to the main rotor, reaches the launcher through the attachment points between the launcher and the helicopter. For the twin launcher the releasing unit hooks and the pressure pads are the attachment points. The response analysis of the launcher system to the broadband random excitation can be treated as a Base Excitation problem. The equations of motion are segregated into the free and restrained (support) Degrees of Freedom (DOF) as:

$$\begin{bmatrix}[M_{ff}] & [M_{fr}]\\ [M_{rf}] & [M_{rr}]\end{bmatrix}\begin{Bmatrix}\{\ddot{u}_f\}\\ \{\ddot{u}_r\}\end{Bmatrix}+\begin{bmatrix}[C_{ff}] & [C_{fr}]\\ [C_{rf}] & [C_{rr}]\end{bmatrix}\begin{Bmatrix}\{\dot{u}_f\}\\ \{\dot{u}_r\}\end{Bmatrix}+\begin{bmatrix}[K_{ff}] & [K_{fr}]\\ [K_{rf}] & [K_{rr}]\end{bmatrix}\begin{Bmatrix}\{u_f\}\\ \{u_r\}\end{Bmatrix}=\begin{Bmatrix}\{F\}\\ \{0\}\end{Bmatrix} \qquad (1)$$

Where, $\{u_f\}$ are the free DOF , $\{u_r\}$ are the restrained DOF that are excited by random loading. The restrained DOF that are not excited are not included in equation (1) $\{F\}$ is the nodal force excitation, which is zero for this base excitation problem.

The free displacements can be decomposed into pseudo-static and dynamic parts as:

$$\{u_f\}=\{u_s\}+\{u_d\} \qquad (2)$$

The pseudo-static displacements may be obtained from equation (2) by excluding the first two terms on the left-hand side of the equation and by replacing $\{u_f\}$ by $\{u_s\}$

$$\{u_s\}=-[K_{ff}]^{-1}[K_{fr}]\{u_r\}=[A]\{u_r\} \qquad (3)$$

in which $[A]=-[K_{ff}]^{-1}[K_{fr}]$ Physically, the elements along the ith column of $[A]$ are the pseudo-static displacements due to a unit displacement of the support DOF excited by the ith base PSD. Substituting equation (2) and (3) into equation (1)

$$[M_{ff}]\{\ddot{u}_d\}+[C_{ff}]\{\dot{u}_d\}+[K_{ff}]\{u_d\}\cong-([M_{ff}][A]+[M_{fr}]\{\ddot{u}_r\})$$

(4)

The term on the right-hand side of equation (4) represents the equivalent forces due to support excitations. Using mode superposition and

$$\{u_d(t)\}=[\phi]\{y(t)\} \qquad (5)$$

equation (4) can be decoupled yielding:

$$\ddot{y}_j+2\zeta_j\omega_j\dot{y}_j+\omega_j^2 y_j=G_j \qquad (j=1,2,3,\ldots.n) \qquad (6)$$

The modal loads G_j are defined by:

$$G_j=\{\Gamma_j\}^T\{\ddot{u}_r\} \qquad (7)$$

The modal participation factors corresponding to support excitation are given by:

$$\{\Gamma_j\}=([M_{ff}][A]+[M_{fr}])^T\{\phi_j\} \qquad (8)$$

Mode shapes $\{\phi_j\}$ are normalized with respect to the mass matrix.

Using the theory of random vibration, the response PSDs can be computed from the input PSDs, with the help of transfer functions for the single DOF systems, $H(\omega)$ and by using mode superposition technique. The response PSD for the ith DOF relative (dynamic) free displacement is given by:

$$S_{d_i}(\omega)=\sum_{j=1}^{n}\sum_{k=1}^{n}\phi_{ij}\phi_{ik}\left[\Gamma_j\Gamma_k H_j^*(\omega)H_k(\omega)S_{inp}(\omega)\right] \quad (9)$$

The transfer function for a single degree of freedom system with displacement as the output and acceleration as the input is:

$$H_j(\omega)=\frac{1}{\omega_j^2-\omega^2+i\left(2\zeta_j\omega_j\omega\right)} \quad (10)$$

Now, random vibration analysis can be used to show that the mean square response of the ith free displacement is:

$$\sigma_{f_i}^{\ 2}=\int_0^\infty S_{d_i}(\omega)d\omega \quad (11)$$

Closed-form solutions for piecewise linear PSD are employed to compute the integration in equation (11). Subsequently, the variance becomes:

$$\sigma_{f_i}^{\ 2}=\sum_{j=1}^{n}\sum_{k=1}^{n}\phi_{ij}\phi_{ik}Q_{jk} \quad (12)$$

Equation (13) represents mode combination of the various vibration modes. Furthermore, the variances of the first and second time derivatives are computed using the following relations:

$$S_{\dot{u}}(\omega)=\omega^2 S_u(\omega) \quad (13)$$

$$S_{\ddot{u}}(\omega)=\omega^4 S_u(\omega) \quad (14)$$

The 1σ response corresponds to the g_{rms} value of the response spectrum

$$\sigma=\sqrt{\sigma_{f_i}^{\ 2}} \quad (15)$$

The mode shapes extracted from the finite element model of the launcher are used to evaluate the random response. All the natural modes in the frequency range of 0–500 Hz, are used for response spectrum analysis. Constant damping ratio corresponding to 2% damping is used for analysis. Sine-on-random PSD as detailed is fed as the input acceleration PSD in g2/Hz. Unit displacement excitation is applied at all the DOF restrained in the finite element model in X,Y and Z directions.

VI. RESULTS & DISCUSSIONS

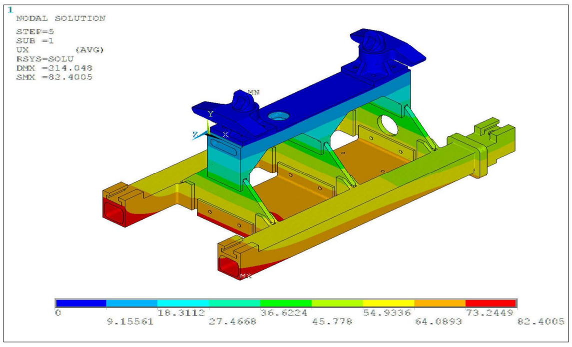
Response displacement and acceleration solutions relative to base excitation are obtained from analysis as described in the section 5B. The maximum 1σ acceleration and 1σ stresses for the launcher, in all the 3 perpendicular direction are tabulated below in Table-3. The 1σ accelerations and stresses for the launcher in all the 3 perpendicular direction are given in Fig. 6 and 7. In critical location acceleration response is with in the limit. Sufficient factor of safety is available. Static analysis was carried out for static (inertial) loading. von-Mises stress plots for all directions are given in Fig. 8. Results of static analysis are given in Table-4. Sufficient factor of safety is available for this load case also.

Table-3: Results of 1σ acceleration and 1σ stresses

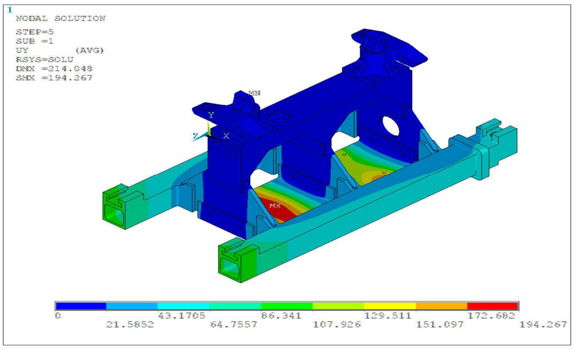
1σ Accelerations (m/s2)			
	X	Y	Z
Launcher	82.4(8g)	194.2(19 g)	54.4 (5.4 g)
1σ Stresses (MPa)			
	X	Y	Z
Launcher	190	195	110
FOS	2.7	2.28	3.6

Table-4: Results of Static analysis

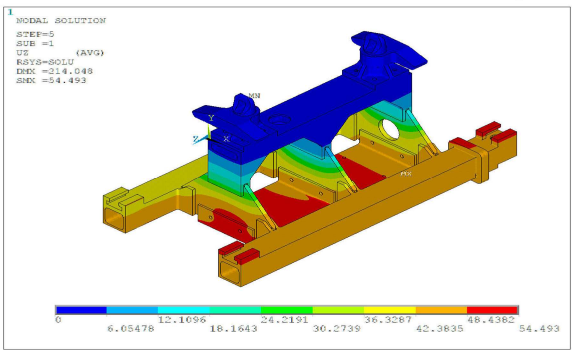
Von-Mises Stresses (MPa)			
	Forward	Sideward	Downward
Launcher	144	209	182
FOS	3.9	2.4	2.9



X-direction (m/s^2) maximum value 8g

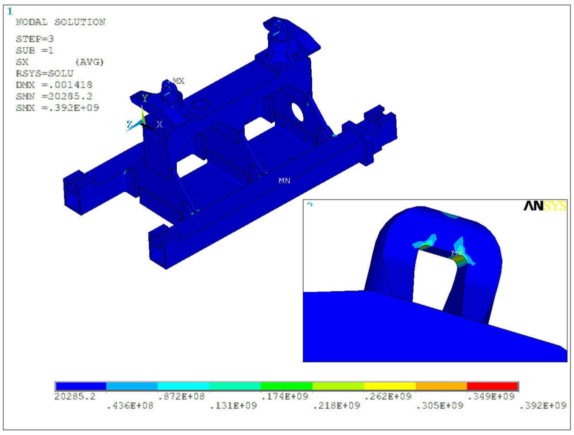


Y-direction (m/s^2) maximum value 19 g

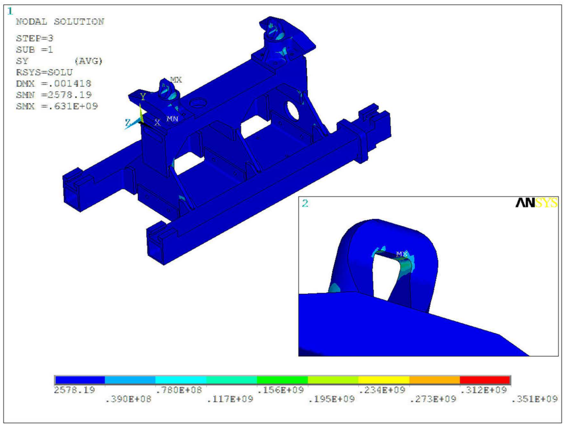


Z-direction (m/s^2) maximum value 5.4 g

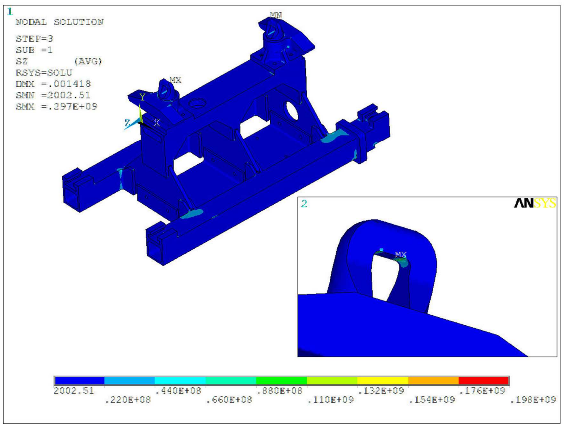
Fig. 6 1σ Acceleration Response of Launcher



X-direction

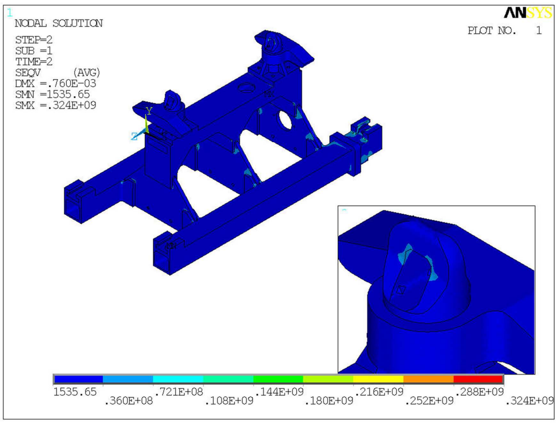


Y-direction

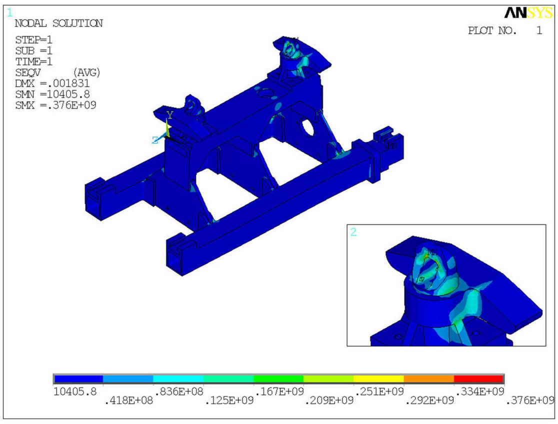


Z-direction

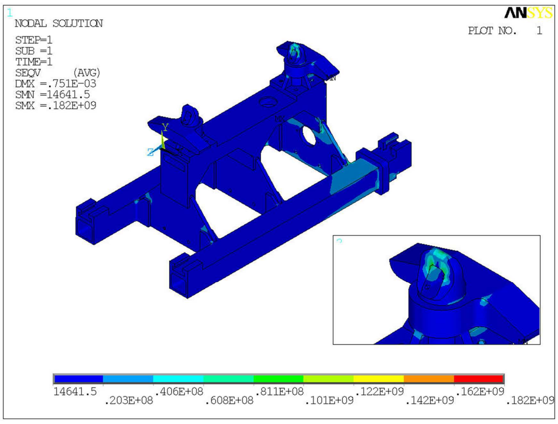
Fig. 7 1σ Stress Response of Launcher



Forward direction



Sideward direction



Downward direction

Fig. 8 vonMises Stress plot of Launcher (static loading)

VII. CONCLUSIONS

In the present study the launcher system has been designed for vibration environment arising out of the rotor induced pressure fluctuations and the harmonic excitation from main rotor frequencies. The design philosophy employed for the design of launcher frame is to avoid a match or a near match of the structural resonant frequencies with the rotor frequencies.

Another prescribed design constraint is that the weight of the launcher frame assembly should not exceed 20 kg. The design weight (estimate) is well within the weight limits (inclusive of studs, thread inserts, nuts, washers, etc.).

The launcher frame is made up of members, having hollow box-type cross-sections. Box-section has been chosen after initial iterations of open I-section indicated low frequency torsion modes. The box-section has high torsion rigidity compared to the open I-section. stress results shows that the launcher has a minimum required factor of safety. The response results shows that the amplifications in amplitudes for vibration input are within the permissible range. The separation has been maintained between launcher frequency and the rotor's critical frequencies. The study demonstrates the need for considering the dynamic design criteria for missile launcher system

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